

Colliding neutrino beams

Reinhard Schwienhorst*

Department of Physics & Astronomy,

Michigan State University, East Lansing, MI 48824, USA

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Abstract

From several neutrino oscillation experiments, we understand now that neutrinos have mass. However, we really don't know what mechanism is responsible for producing this neutrino mass. Current or planned neutrino experiments utilize neutrino beams and long-baseline detectors to explore flavor mixing but do not address the question of the origin of neutrino mass. In order to answer that question, neutrino interactions need to be explored at much higher energies. This paper outlines a program to explore neutrinos and their interactions with various particles through a series of experiments involving colliding neutrino beams.

*Electronic address: schwier@pa.msu.edu

I. INTRODUCTION

Neutrinos were first introduced to preserve the law of energy conservation in nuclear beta decay. The first experimental studies of neutrinos came with the advent of neutrino beams [1]. The understanding of neutrinos had been limited to their role in weak interactions, where they participate as massless left-handed leptons. In the Standard Model (SM), neutrinos have been massless for the longest time. Several experiments involving atmospheric [2], solar [3, 4], and accelerator neutrinos [5, 6] have changed that picture recently. We now understand that neutrinos have masses, albeit small, and that the mass Eigenstates are not Eigenstates of the weak interaction and thus neutrinos undergo flavor oscillations. This picture is rather similar to the quark sector where mixing between generations has been studied for several decades. In the quark sector, experiments are now starting to explore not only details about this flavor mixing but also the actual mechanism that produces quark masses, i.e. the Higgs mechanism. Within the SM, the Higgs mechanism is responsible for electroweak symmetry breaking and fermion masses [7]. But the Higgs boson hasn't been observed yet and is not the only possible mechanism leading to particle masses. There are many other theories that could explain electroweak symmetry breaking and the generation of particle masses. Searches are currently underway at the Fermilab Tevatron for direct production of the Higgs boson, both within the SM [8, 9, 10, 11, 12, 13], and from theories beyond the SM [14, 15, 16, 17, 18, 19, 20, 21]. Moreover, the LHC proton-proton collider at Cern will start operating soon and is expected to reveal the electroweak symmetry breaking mechanism [22, 23, 24, 25].

For neutrinos, no such program to understand the origin of their mass exists or has even been thought of. There is no theoretical physics reason for the same mass generation mechanism to apply to neutrinos and other fermions of the SM [26, 27, 28, 29, 30]. It is not clear at all that neutrinos acquire mass in the same way as quarks because the mass scales are so different between neutrinos and quarks and even between neutrinos and their partner leptons. And not only are neutrino masses significantly smaller than their partner lepton masses, but only left-handed neutrinos participate in weak charged current interactions [31].

The current focus for experimental neutrino physics is to understand the parameters of neutrino flavor oscillations [32]. Several experiments are currently running or approved that will study neutrino oscillations in more detail: K2K [5], Minos [33], and Cern to

Gran Sasso [34]. All these experiments intend to address the lepton-equivalent of the CKM matrix. However, none of them can reveal the actual mechanism that is responsible for neutrino masses. Some ideas of looking for production of Majorana neutrinos at hadron colliders such as the LHC have been proposed [35], but those look for new particles produced in the weak interaction rather than actually testing the neutrino mass generation mechanism. Similarly, there are several experiments looking for neutrinoless double-beta decay, which would provide a measurement of the absolute scale of neutrino masses and establish the existence of Majorana neutrinos (see [36] and references therein). However, all of them look for evidence of a Majorana neutrino participating in the weak interaction and none of them probe the actual neutrino mass generation mechanism directly.

Observing the mass generation mechanism directly means looking for new particles that couple to neutrinos and possibly observing Yukawa interactions of neutrinos. And so far, there has not been any idea or proposal to accomplish this. In fact, the only neutrino interactions that have been observed so far have been weak interactions, neutrino couplings to the W and Z bosons. Of course, within the SM neutrinos are massless and no other interactions exist. But since neutrinos have non-zero mass, neutrino interactions other than through the weak interaction must exist. They arise from physics beyond the SM, involving new particles, symmetries, and interactions. Moreover, since they have mass, neutrinos may have $V+A$ couplings besides the SM $V-A$ coupling. In order to reach the energies required to observe such interactions and produce most of these new particles, high-energy neutrino beams are required, and neutrino collisions with sufficient center of mass energy to produce these particles directly. In this paper, we describe how colliding neutrino beams can be used to explore neutrino interactions at the highest energies and possibly reveal the neutrino mass generation mechanism.

Neutrino beams were initially proposed to study the weak interaction [1, 37, 38]. Neutrino beams have also been used to study the structure of nuclear matter. High-statistics neutrino experiments have mapped out the parton composition of nuclei [39, 40, 41, 42, 43, 44]. These experiments have always used complex nuclei in order to have large target mass. Similarly, neutrino-electron scattering results have been obtained by directing neutrino beams onto targets and then extracting electron scattering events from the large background of nuclear scattering events [45].

The configurations outlined below collide neutrinos with protons, electrons, muons and

other particles, many for the first time. We will show that while neutrino energies that can be reached with current accelerators are sufficient to study neutrino interactions at the highest energies, currently achievable luminosities are not. Future accelerators such as a neutrino collider based on muons storage rings are required to achieve significantly higher luminosities and study neutrino-neutrino interactions for the first time.

II. PHYSICS WITH COLLIDING NEUTRINOS

The experimental focus for neutrinos so far has been on relatively low energies compared to beams of other particles (electrons or protons). A neutrino energy range of a few GeV is well suited to study neutrino oscillations, but doesn't help much when trying to observe neutrino collisions or reveal the underlying mechanism that generates neutrino masses. In order to explore potential new interactions and particles, high energy neutrino beams are required so that the center-of-mass energy is sufficient to produce possible new particles directly. Within the SM, the largest interaction rate in neutrino colliders is due to W boson exchange, between neutrinos from one beam and a particle (proton, electron, muon, or neutrino) from the other beam. The cross section for these electroweak charged current interactions is small, thus primary beams of unprecedented intensity will be needed. The interactions are straightforward to detect in a typical high-energy detector because each interaction produces a high-momentum muon (or electron) that tags the interaction.

Colliding neutrinos with beams of other particles has two main advantages over fixed target experiments. The first one is the obvious increase in the center-of-mass energy. For a neutrino beam incident on a fixed target, the center-of-mass energy is roughly the square root of the beam energy. By contrast, colliding beams have a center-of-mass energy of twice the beam energy. While low energy beams and collisions can be used to study properties of matter and investigate neutrino mixing, they are not sufficient to produce heavy objects like W or Z bosons directly. In order to reach the energies required to produce not only the heavy bosons but also potentially new (and heavier) particles, much higher center-of-mass energies are required. The second advantage is that the interacting particles are only those present in the beams rather than the complex nuclear structure of a fixed target. In particular, colliding neutrino and electron beams allows for the first low-background study of neutrino-electron interactions without having to worry about nuclear matter. And finally,

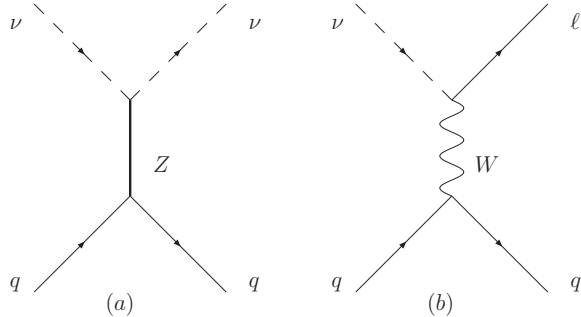


Figure 1: Feynman diagrams for neutrino-quark collisions in the SM. Shown are (a) the t -channel exchange of a Z boson and (b) the t -channel exchange of a W boson.

colliding a neutrino beam with a muon beam allows for the first ever study of neutrino-muon collisions, something that is not possible in a fixed-target experiment.

These collisions of neutrinos with other particles can be useful to study not just the weak interaction or properties of the particles involved but also to search for new physics in the coupling between neutrinos and other matter.

A. Neutrino-quark interactions

In neutrino-proton interactions, it is actually the W boson that probes the structure of the proton, equivalent to the HERA electron-proton collider where a photon probes the structure of the proton [46]. Along these lines, a neutrino beam colliding with a proton beam can serve to measure parton distribution functions of the proton. Moreover, one is not restricted to proton beams and could also collide neutrinos with pion or kaon beams, for example. Such a collider enables the first direct study of the structure of mesons from a weak interaction perspective. And one could in principle also imagine colliding neutrino beams with heavy ion beams, although heavy nuclei have already been studied in detail with neutrino beams incident on nuclear targets.

Fig. 1 shows the relevant Feynman diagrams for SM neutrino-proton collisions. A quark from the proton exchanges a Z or W boson with the neutrino, leading to a final state of only a quark jet or a lepton plus quark jet. Experimentally, the lepton produced in the W boson exchange can be used to identify the interaction, making it straightforward to select neutrino-quark charged current scattering events.

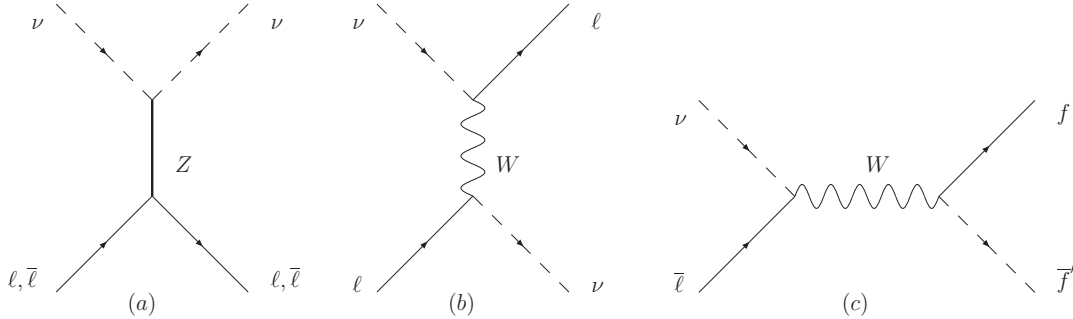


Figure 2: Feynman diagrams for neutrino-lepton collisions in the SM. Shown are (a) the t -channel exchange of a Z boson, (b) the t -channel exchange of a W boson, and (c) the s -channel production of a W boson with decay to a fermion-antifermion' pair.

B. Neutrino-lepton interactions

Within the SM, neutrinos interact with leptons either through charged current W boson exchange or through neutral current Z boson exchange. Several different Feynman diagrams contribute, as shown in Fig. 2.

The exchange of a Z boson is always possible for any combination of beam particles (neutrino or antineutrino colliding with electron or positron, Fig. 2 (a)). If the neutrino beam and the lepton beam are both particles (or both antiparticles), then the t -channel exchange of a W boson is also possible (Fig. 2 (b)).

If the neutrino beam and the lepton beam are particle-antiparticle pairs of the same flavor, then s -channel annihilation into a W boson is allowed, which leads to a final state typical for W boson decay of either lepton-neutrino pair or quark-jet pair (Fig. 2 (c)). Since neutrinos undergo flavor mixing, this annihilation also occurs for neutrino and lepton beams of different families.

For example, in a muon neutrino-antimuon collider, the muon neutrino annihilates with the antimuon to form a W boson. The decay of this W boson produces the typical signature of either two quarks or one lepton and missing transverse energy, both of which are straightforward to identify in a detector. In both cases the W boson can be reconstructed from the final state particles, although in the case of the lepton+neutrino final state only the transverse components of the neutrino momentum can be reconstructed due to the wide spread of beam neutrino momenta. There are also t -channel exchanges of Z bosons and

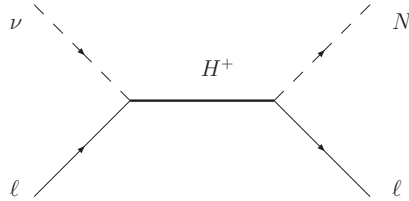


Figure 3: Example Feynman diagram for s -channel production of a charged Higgs boson which subsequently decays to a heavy neutrino and a lepton.

W bosons between the neutrino and the lepton (Figs. 2 (a) and (b)). These interactions also produce a final state of a lepton and neutrino, but both lepton and neutrino are more in the forward direction and there is no resonance invariant mass peak. Thus these interactions are harder to identify in a detector.

Models of new physics that have higher order symmetries result in additional heavy W' and Z' bosons [47]. If these new bosons couple only to the lepton sector and not the quark sector, then a neutrino-lepton collider is especially sensitive to them. The interactions are the same as shown in Fig. 2, but replacing the exchange W and Z bosons by heavier W' and Z' bosons.

A neutrino-lepton collider is able to produce heavy Dirac or Majorana neutrinos through the exchange of neutral or charged Higgs bosons that arise in many models of new physics, as shown in Fig. 3 [48, 49, 50]. The figure shows the production of a charged Higgs boson which then decays to a heavy neutrino and a lepton. These interaction vertices are similar to those possible at electron colliders [51, 52], except that here a neutrino appears in the initial state. If the right-handed neutrino has weak interactions, then the production of a heavy right-handed neutrino in the decay of a W boson is also possible.

C. Neutrino-neutrino interactions

Colliding neutrinos with other neutrinos is not only a sensitive probe to new physics involving neutrinos but also allows for SM measurements that would otherwise not be possible. In particular, a measurement of the total Z boson production rate in neutrino collisions provides a direct measurement of the neutrino coupling to the Z boson. This coupling has only been measured indirectly so far, in single-photon production [53, 54] as well as in Z boson decays through a measurement of the total Z decay width and in neutrino-nucleon neutral

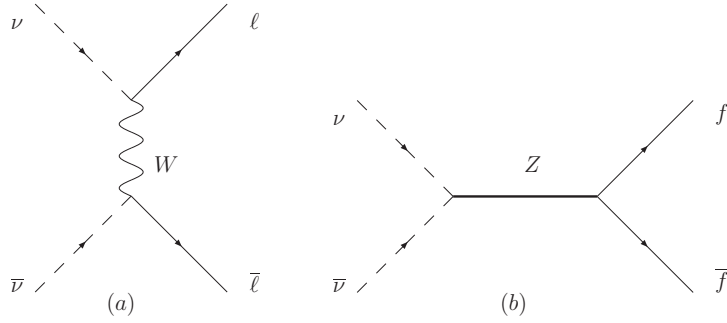


Figure 4: Feynman diagrams for neutrino-neutrino collisions in the SM. Shown are (a) the t -channel exchange of a W boson and (b) the s -channel production of a Z boson with subsequent decay to a fermion pair.

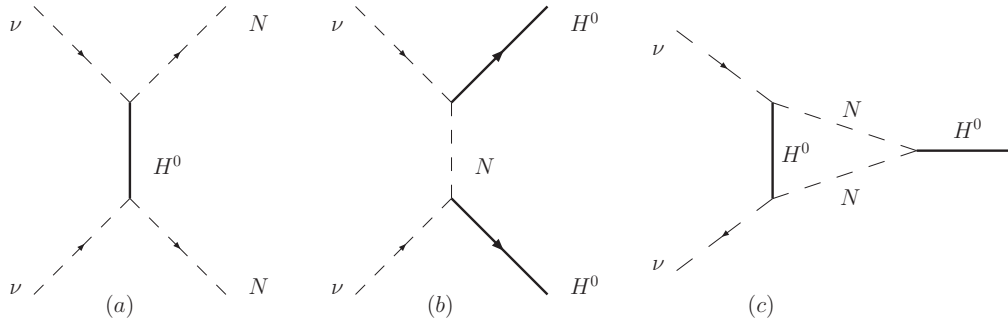


Figure 5: Example Feynman diagrams for neutrino-neutrino collisions involving heavy neutrinos. Shown are (a) the t -channel exchange of a Higgs boson, (b) the t -channel exchange of a heavy neutrino, and (c) the resonance production of a Higgs boson through a loop involving the Higgs boson and heavy neutrinos.

current scattering experiments [55]. A neutrino-antineutrino collider probes this coupling directly through the annihilation of neutrino and antineutrino into a Z boson.

A large event rate in neutrino-antineutrino collisions is due to W boson exchange between two neutrinos. This results in a final state of two oppositely charged leptons which are straightforward to observe. This is also the final state that can be used to establish the existence of collisions when neutrino colliders are turned on for the first time and the luminosity is relatively low. There is also a neutral current Z boson t -channel exchange between the two neutrinos, but since the final state consists of two neutrinos, this interaction will not be observable.

All of the interactions and beam configurations discussed so far are sensitive to new

physics in the neutrino sector. But colliding neutrinos with antineutrinos has more potential to observe new physics due to the possibility of producing new particles. Just as in the case of a neutrino-lepton collider, heavy copies of the SM W and Z bosons can contribute through diagrams as shown in Fig. 5. Two more examples are shown in Fig. 5. In Fig. 5 (a), a new Higgs boson that couples mainly to neutrinos (H^0) is being exchanged between the two incoming neutrino beams, leading to a final state of two heavy neutrinos. Similarly, Fig. 5 (b) shows the exchange of a heavy neutrino leading to a final state of two Higgs bosons. These two processes are in particular interesting to distinguish whether the heavy neutrino is of Dirac type or Majorana type. If it is a Majorana neutrino, then it couples both to neutrinos and antineutrinos, and thus the final state heavy neutrinos in Fig. 5 (a) are indistinguishable, leading to lepton-flavor violation and final states of like-sign events. Along the same lines, the incoming neutrinos don't have to be of opposite flavor, thus the cross section is enhanced at a neutrino-neutrino collider.

Exploring the mechanism that gives neutrinos masses should start after the LHC will hopefully have revealed the origin of quark masses. A new model of quark masses should emerge from the LHC measurements and possibly from precision measurements at the next linear collider. Any neutrino collider such as described in this paper will not be set up until after the LHC has yielded results. Thus, an important aspect of neutrino colliders will be to observe interactions predicted by the new theory and to check if neutrinos fit into the picture that will emerge from the LHC era. We don't know yet what the LHC will bring, but new physics is generally expected to appear at the TeV scale, within reach of the LHC, and quite possibly within reach of a neutrino collider. And producing heavy neutrinos, Higgs bosons, and other new particles in neutrino colliders is really the only method to observe the neutrino mass generation mechanism directly. There may also be surprises awaiting at higher energies where the SM is expected to break down.

Moreover, neutrino beams are 100% polarized by nature, and that feature can be exploited. Angular correlations between the two leptons produced in the W boson exchange process can for example be used to study the nature of the weak interaction and the coupling of the W boson to neutrinos. They can also be used to look for right-handed neutrinos in the beam.

III. NEUTRINO BEAMS

Neutrinos by themselves cannot be accelerated, accumulated, or stored in a magnetic storage ring. In order to produce a neutrino beam, it is necessary to accumulate, store, and accelerate charged particles which then in turn produce the neutrino beam. Once produced, the neutrino beam cannot be manipulated further.

A. Neutrinos from proton beams

All of the neutrino beams used in modern oscillation experiments are produced in the same fashion: High-energy protons hit a stationary target and the resulting pions and kaons are allowed to decay to muons and muon neutrinos in a long decay pipe. Some of the muons decay further to electrons, electron neutrinos, and muon antineutrinos. Strong magnetic fields are used to focus the pions and select pions of a certain charge and momentum. The dominant decay process is $\pi^+ \rightarrow \mu^+ \bar{\nu}_\mu$. Some of these muons decay further, $\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e$, which means a neutrino beam produced by protons always contains a mixture of neutrinos. Nevertheless, selecting positively charged pions results in a beam consisting predominantly of anti-muon-neutrinos, and selecting negatively charged pions results in a beam consisting predominantly of muon-neutrinos. The neutrino beam energy spectrum is not uniform. The spectrum is rather broad and varies with neutrino flavor due to the decay chains involved. The mean neutrino energy is much lower than the incident proton beam energy.

For wide-band neutrino beams used in neutrino-nucleon scattering experiments, neutrino interactions have been observed for neutrino energies up to about half the incident proton energy [56]. Despite the relatively small number of these high energy neutrinos, their interactions can nevertheless be observed because the linear rise in cross section with neutrino energy compensates for the falling spectrum. The reach in neutrino energy and thus the physics potential for neutrino beams is driven by the incident proton energy. Still, most of the interacting neutrinos have less than about 10% of the initial proton energy.

Since this article focuses on colliding high-energy beams, only the neutrino beams at Fermilab and at Cern will be addressed. While there are more neutrino beams in operation or planned, at KEK [57] and other facilities, those all utilize lower energy to explore specific aspects of neutrino flavor oscillations.

At Fermilab, the current Minos neutrino beam is produced from 120 GeV protons extracted from the main injector incident on a graphite target. The neutrino beam energy can be selected with two focusing horns. In what is called the high-energy running mode, this results in typical mean neutrino energies of around 10 GeV, with neutrino energies extending up to about 20 GeV [58].

At Cern, it is planned for the CNGS neutrino beam to be produced by 400 GeV protons extracted from the SPS incident on a graphite target. Subsequent focusing results in a mean neutrino energy of about 25 GeV, with a tail extending out to about 50 GeV [34].

The highest energy neutrino beam in operation so far has been the Fermilab wide band neutrino beam used by the CCFR experiment [56]. It was produced by 800 GeV protons incident on a production target, with quadrupole magnets focusing a wide band of secondary particles onto the experiment. The mean energy for the Fermilab wide band beam was about 80 GeV, but interactions due to neutrinos of up to about 500 GeV were observed.

Based on the discussion above, it is easy to see how high-energy neutrino beams could be constructed at Fermilab and at Cern. At Fermilab, protons from the Main Injector are already being used to produce a neutrino beam, but in order to reach higher energies, the Tevatron needs to be set up in a new high-energy neutrino beam configuration. At Cern, the SPS can be used to produce a wide-band neutrino beam (rather than the lower energy beam that is currently planned for CNGS). But to reach even higher energies, the highest energy accelerator, the LHC, needs to be reconfigured to produce neutrino beams. We will propose specific beam configurations in this paper.

Since every pion decay produces not only a neutrino but also a partner muon, these proton-produced neutrino beams have associated muon beams with energy distribution and beam parameters comparable to the neutrino beam itself. This is a serious challenge when it comes to the detector setup, because the muons penetrate the interaction region, the detector, and even interact with the detector material. It will be important to separate interactions caused by muons from interactions caused by neutrinos in the detector. The muons don't all have to be absorbed before they decay (such as required for a long-baseline neutrino beam), but they need to be deflected away from the neutrino interaction region. The associated muon beam will be discussed further in Sec. sub:muonbeam.

1. *Tevatron*

The Fermilab Tevatron has been used in the past to produce a high-energy neutrino beam from 800 GeV protons incident on a Beryllium target. The Tevatron currently accelerates protons and antiprotons to 980 GeV each and then collides them in two interaction regions. It should be possible to extract the protons at 980 GeV from the Tevatron and direct them onto a target as shown in Fig. 11.

The number of neutrinos produced by such a beam can be calculated assuming a similar layout to the current NuMI beamline. The existing Main Injector neutrino beamline accepts 5 bunches of protons from the Booster per 0.45 Hz spill, each bunch containing 5×10^{12} protons [58]. Work is currently underway to double this number [59]. An increase in the number of protons by another order of magnitude is currently being studied in the context of neutrino superbeams. This requires a high-intensity proton driver to deliver significantly more protons into the accelerator complex. Thus, we assume as a baseline that the Tevatron can produce a proton beam containing 10^{14} protons per bunch and provide 5×10^7 bunches per year.

The parameters of the resulting neutrino beam have been calculated with the `bmpt` program [60]. For simplicity, the target parameters have been taken as the default `bmpt` settings, which refer to the CNGS neutrino beam [34]. Only the parameters for incident proton energy, pion decay tunnel length, detector distance, and detector radius have been adjusted. The incident proton beam energy is set to 980 GeV and the proton target is made of carbon.

Fig. 6 shows the neutrino flux in a small cross section area with 1 cm radius as a function of the distance to the proton target. The optimal interaction point is at a location between 100 m and 200 m downstream of the production target. At shorter distances the decay tunnel is too short for enough pions to decay, while at larger distances the neutrino beam diverges too much. The flux maximum is fairly broad however, which makes the placement of the different components flexible.

For the following calculations we choose a 200 m long decay tunnel which contains two focusing magnets. Downstream of the decay tunnel is a 10 m thick shielding wall. This space should also contain magnets to deflect muons and pions and other charged particles away from the interaction region. The radial profile of the neutrino beam at this location is

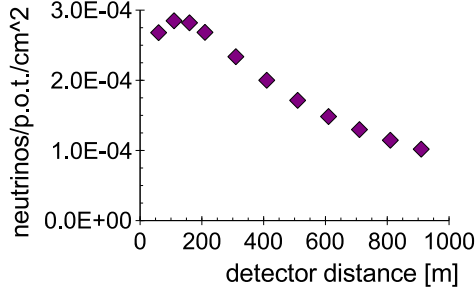


Figure 6: Neutrino flux in a circular region with radius 1 cm as a function of the distance to the proton target, for a proton beam of 980 GeV, for optimal secondary particle focusing and a decay tunnel that is 10 m shorter than the detector distance.

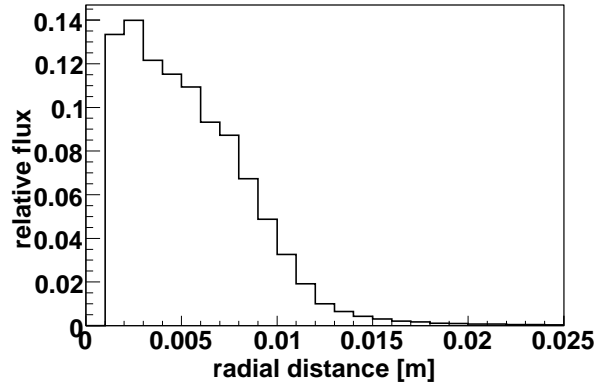


Figure 7: Radius of the neutrino beam at a distance of 210 m downstream of a proton target for the Fermilab Tevatron beam, extracted at 980 GeV.

shown in Fig. 7. The initially point-size beam spreads out to a radius of about 1 cm.

Henceforth, the vertical dimensions of the neutrino interaction region will be set to a radius of 1 cm. This is a significantly larger beam size than in typical charged particle colliders, but is unavoidable because the neutrinos themselves cannot be focused.

The neutrino energy spectrum in this configuration is shown in Fig. 8. The spectrum is falling quickly and there are almost no neutrinos left with energies above 120 GeV. The mean neutrino energy is 30 GeV.

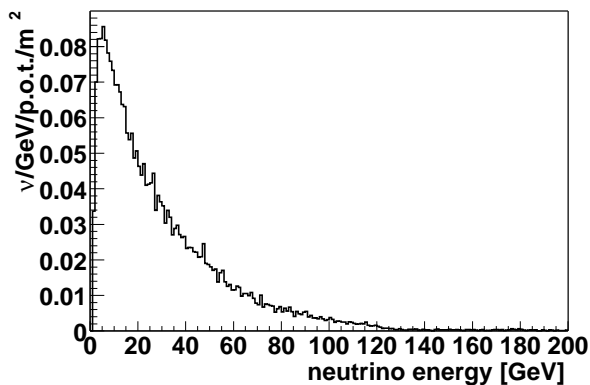


Figure 8: Neutrino energy at a distance of 210 m downstream of a proton target for the Fermilab Tevatron beam, extracted at 980 GeV.

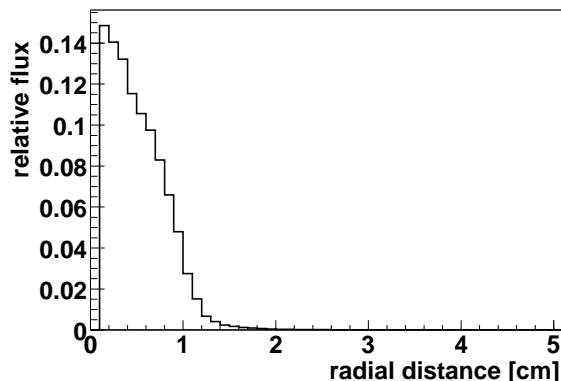


Figure 9: Radial profile of the neutrino beam at a distance of 210 m downstream of a proton target in the LHC configuration.

2. LHC

The LHC will accelerate protons to 7000 GeV and collide those in four separate interaction regions. Using these protons to produce neutrinos will result in a high-intensity, high-energy neutrino beam. The radial distribution of such a neutrino beam at a distance of 210 m is shown in Fig. 9. The Gaussian width is about 0.5 cm. The beam is more focused than the Tevatron neutrino beam due to the higher incident proton energy.

The neutrino energy distribution resulting from a 7000 GeV proton beam is shown in Fig. 10, again using the BMPT program with a detector at a distance of 210 m. The neutrino energy spectrum is very similar to the Tevatron, but shifted to higher energies,

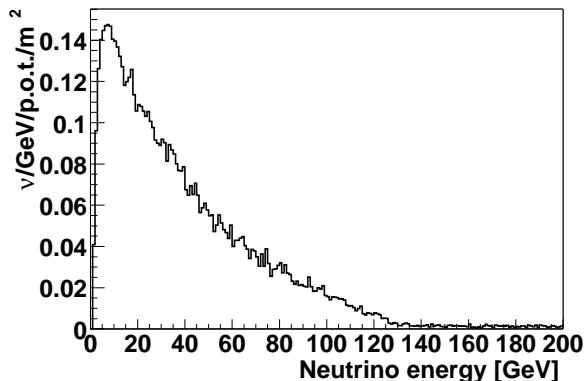


Figure 10: Neutrino energy at a distance of 210 m downstream of a proton target for the LHC beam, extracted at 7000 GeV.

with a mean energy of about 40 GeV.

B. Neutrinos from muon beams

If muons are accelerated to very high energies, then their decay $\mu \rightarrow e\bar{\nu}_e\nu_\mu$ produces a high energy, high intensity neutrino beam. Accelerating muons rather than protons results in significantly more neutrinos at significantly higher energies. Since the neutrinos originate from the muon decay, a large fraction of the initial beam energy is transferred to the neutrinos and much higher neutrino energies can be accomplished with muon beams than with proton beams of comparable energy. Conversely, muon beams don't have to be accelerated to as high of an energy in order to obtain similar neutrino beam energies as obtained by a proton beam. There has been a lot of excitement in recent years about muon accelerators and their potential in producing neutrino beams. Neutrino factories are envisioned that utilize muon storage rings to produce high-intensity neutrino beams [61, 62]. A detailed study of the Physics potential of a neutrino superbeam produced by muons was carried out [63]. Much of the infrastructure required for this neutrino beam is also needed for a muon collider, and one facility might be able to provide both. As will be seen below, a neutrino superbeam can be used not only in fixed-target experiments but also in a collider configuration.

The muons are produced from a proton beam incident on a stationary target. They are then collected, accelerated, and put into the storage ring which has a long straight section. Muon decays in the straight section result in an intense and well-focused neutrino beam.

The beam intensity for such neutrino beams is significantly higher than those discussed above due to the acceleration of the muons. Current estimates give a yield of about 0.1 to 0.2 muons per proton [64]. The same proton drivers as mentioned above thus yields approximately 10^{13} muons per bunch in the accelerator. About a third of them decay in the straight section. The resulting neutrino beam is tightly focused, much better than from proton machines due to the better focusing of the decay particles and the Lorentz boost. Most of the neutrinos pass through an interaction region with a radius of about 1 mm located immediately downstream of the straight section. Such a configuration yields about 10^{12} neutrinos per bunch of 10^{14} protons. The energy distribution of the neutrino beam from such an arrangement are given in Ref. [61]. Due to the muon decay kinematics, the muon neutrino energy peaks close to the muon beam energy for neutrinos that travel within a small angle of the original muon beam.

C. Neutrinos from pion beams

If a muon collider is not the ultimate goal, then accelerating pions has significant advantages over accelerating muons. Pions are by far the most abundant particle produced when a proton beam hits a beam dump. Thus, it might be easier to construct a pion accelerator than a muon accelerator. At the same time, many of technical challenges are common to pion and muon accelerators, in particular the short lifetime of the accelerated particles. Thus, a pion accelerator could provide a first step towards a muon accelerator. Similar to muon beams, neutrinos are produced in the decay of pions, and hence one could construct neutrino superbeams based on pion beams. However, no such accelerator is currently being planned, and neutrinos from pion beams will not be discussed further in this paper.

IV. COLLIDING NEUTRINOS

Since neutrino beams are produced by accelerating charged particles rather than the neutrinos themselves, any neutrino beam facility will also have associated beams of charged particles. It is possible to utilize these in conjunction with the neutrino beam. This leads to two basic colliding neutrino beam configurations.

1. Colliding neutrinos with other particles such as protons and electrons or even pions

and muons. As discussed in Section III, the associated beams are not only needed but also have higher energy than the actual neutrino beam. One exception is an electron beam which would need to be constructed separately.

2. Colliding neutrinos with neutrinos. This configuration could involve neutrinos of the same flavor or of a different flavor. The neutrino beams discussed below all contain a mixture of flavors.

The rate of neutrino interactions R_{event} in a colliding beam setup is calculated from the cross section σ for a given process as

$$R_{event} = \mathcal{L}\sigma,$$

where the luminosity \mathcal{L} is given by

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}. \quad (1)$$

Here, N_1 and N_2 are the number of particles in the two beams, and σ_x and σ_y are the Gaussian widths of the interaction region in the plane perpendicular to the beam direction [31].

In the following, we use the Madgraph program to estimate cross sections for various processes [65]. The neutrino energy spectra from Figs. 8 and 10 have been added to Madgraph in parametrized form. The neutrino energy distribution from a muon collider are based on Ref. [61] and have also been added to Madgraph in parametrized form.

A. Colliding neutrinos with protons

We assume that the same proton beam that produces the neutrinos is also used in neutrino-proton collisions.

1. Tevatron

The Fermilab accelerator complex can be set up to collide neutrinos with protons circulating in the Main Injector in a straightforward way. Fig. 11 shows this arrangement, which uses the same proton beam in the collisions and the neutrino production. Using the same parameters as in Sec. III A 1, the proton beam contains 10^{14} protons per bunch. However,

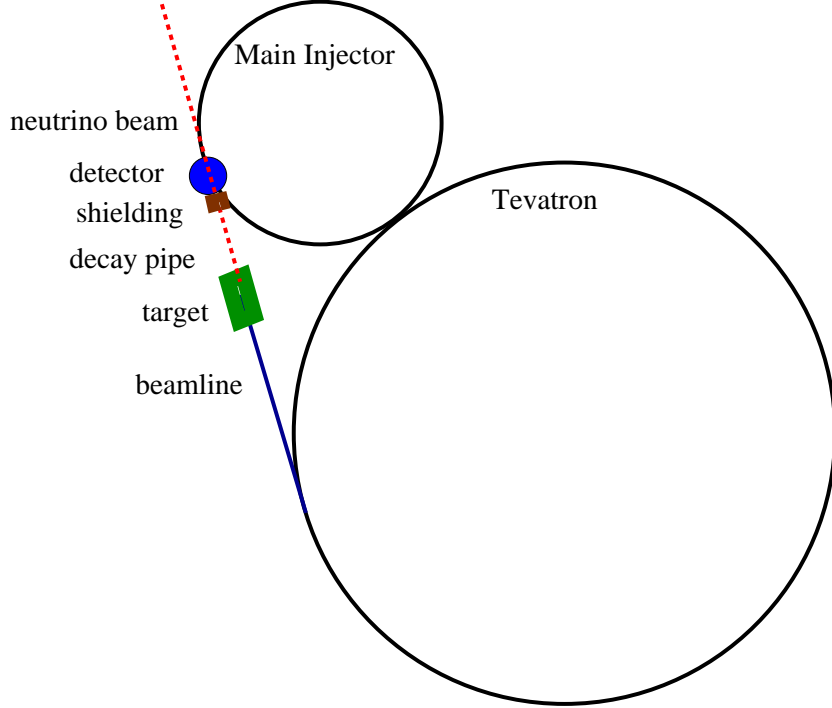


Figure 11: Layout of the Fermilab accelerator complex as a neutrino collider, extracting protons from the Tevatron and directing them onto a target such that the resulting neutrino beam collides with the proton beam circulating in the Main Injector.

it has a significantly smaller cross section area than the neutrino beam. This results in an instantaneous luminosity of $4 \times 10^{23} \text{ cm}^{-2}$ for each collision of a neutrino bunch with a proton bunch. Assuming 5×10^7 bunches per year, and that each neutrino bunch collides with one proton bunch, yields an integrated luminosity of $20 \mu\text{b}^{-1}$ per year. The neutrino-proton weak interaction cross section for the parameters given above is $1.5 \times 10^{-3} \mu\text{b}$, calculated with the Madevent program [65]. Hence at this luminosity there are about 0.03 neutrino-proton interactions per year, or 3 interactions every 100 years.

Reaching luminosities required for reasonable event samples on the order of several pb^{-1} (for example comparable to the startup of the HERA electron-proton collider [66, 67]) requires an increase in the proton intensity by about two orders of magnitude to 10^{16} protons per bunch. Such intensities result in a few thousand neutrino-quark charged current scattering events per year, sufficient for initial studies. Over time, the intensity will need to be increased even further to reach much higher integrated luminosities required to start detailed studies of neutrino-proton interactions at the highest energies.

Alternatively, if a muon storage ring is built at Fermilab, then neutrinos from this beam can be directed onto the Tevatron proton beam. According to Eq. 1, with two beams that are each about 1 mm in size, an instantaneous luminosity of about $8 \times 10^{26} \text{cm}^{-2}$ can be reached. Assuming that such an accelerator setup could also collide 5×10^7 bunches each year gives an integrated luminosity of 4pb^{-1} per year. This is a factor 2000 higher than the setup with a Tevatron-based neutrino beam described above, mainly due to the significantly smaller transverse size of the interaction region. This will be sufficient for initial studies. If the intensity of both the proton and muon beams is increased by another order of magnitude then several hundred pb^{-1} can be collected each year allowing for high-statistics physics studies.

2. LHC

If the LHC is configured to direct the 7000 GeV proton beam onto a production target then the resulting neutrino beam can be directed at the SPS accelerator where the neutrinos would collide with 450 GeV protons. This configuration is equivalent to the Fermilab Tevatron-Main Injector setup, but the corresponding energies are higher. The neutrino-proton cross section increases to $6.9 \times 10^{-3} \mu\text{b}$, where the calculation again uses the Madgraph program and the neutrino energy spectrum shown in Fig. 10. Since the LHC hasn't started running yet and will take quite a few years to complete its physics program, reaching proton beam intensities of 10^{16} protons per bunch might become realistic by the time the neutrino beam could be built.

B. Colliding neutrinos with leptons

1. Tevatron

In order to collide the neutrino beam with particles other than protons at the Tevatron or LHC, these particles will need to be produced and accelerated separately. They cannot be part of the proton acceleration process. At the Tevatron, there is already a second accelerator located in the same tunnel as the Main Injector, and that is the Recycler. If the Recycler can be converted to accelerate electrons rather than storing antiprotons, then it becomes possible to collide neutrinos produced by the Tevatron beam with electrons. The electron

beam wouldn't be of very high energy, but energies above 20 GeV might be achievable and should already be sufficient for interesting physics studies.

The resonance production of W bosons from neutrinos and electrons according to Fig. 2 (c) has a cross section of the order of $1pb$ at such a collider. The challenge is thus to produce a high intensity electron beam in order to obtain reasonable interaction rates. For example, in order to reach luminosities of several pb^{-1} , the beam needs to contain more than 10^{18} electrons per bunch, which is about seven orders of magnitude higher than what has been accomplished in past electron-positron colliders [31]. Producing such a very-high intensity electron beam requires significant technological advances. Thus neutrino-electron colliders are not likely to be feasible in the near future, even if the intense neutrino beams become a reality.

2. Muon storage ring

A neutrino-muon collider based on a muon storage ring solves this problem. It can provide much higher CM energy and luminosity. It provides a both the high-energy muon beam and the neutrino beam. An example layout that works with a single muon beam is shown in Fig. 12.

In this configuration, the resonance production of W bosons is not allowed because of the $\mu\nu_\mu$ initial state. The main SM process is the t -channel exchange of a W boson, see Fig. 2 (b). The cross section for this process is shown in Fig. 13.

Since the neutrinos were produced from the same beam they are colliding with and hence have the same flavor, annihilation into a W boson is not possible, only t -channel exchange of a W boson. This is reflected in the relatively low cross section. The distribution is shown as a function of beam energy rather than CM energy because in contrast to the muon, the energy of the initial state neutrino is not known.

If instead two muon beams are used, as shown in Fig. 18 below, then neutrinos collide with anti-muons or vice versa, making resonance W boson production possible. The cross section for this process is shown in Fig. 14.

The cross section for this process as a function of the muon beam energy is shown as the solid line in Fig. 14. While there is no sharp resonance peak due to the spread in neutrino energies, the cross section nevertheless shows a clear peak.

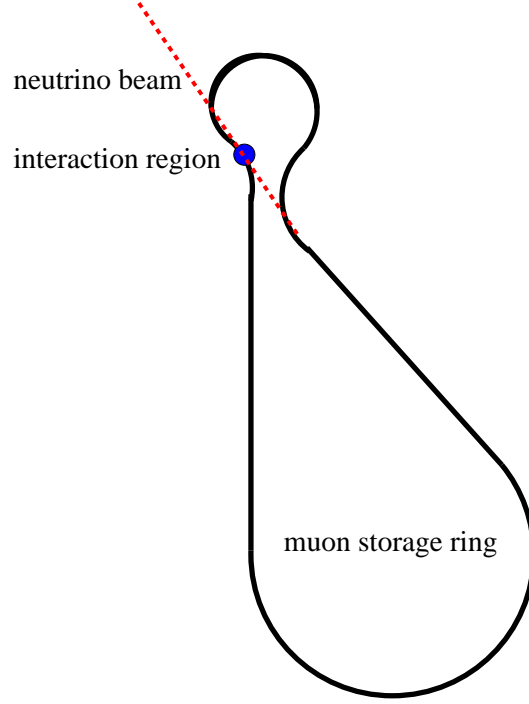


Figure 12: Neutrino-lepton collider based on a muon storage ring. There is only one muon beam circulating in the storage ring. The neutrino-muon interaction region is indicated by the small circles.

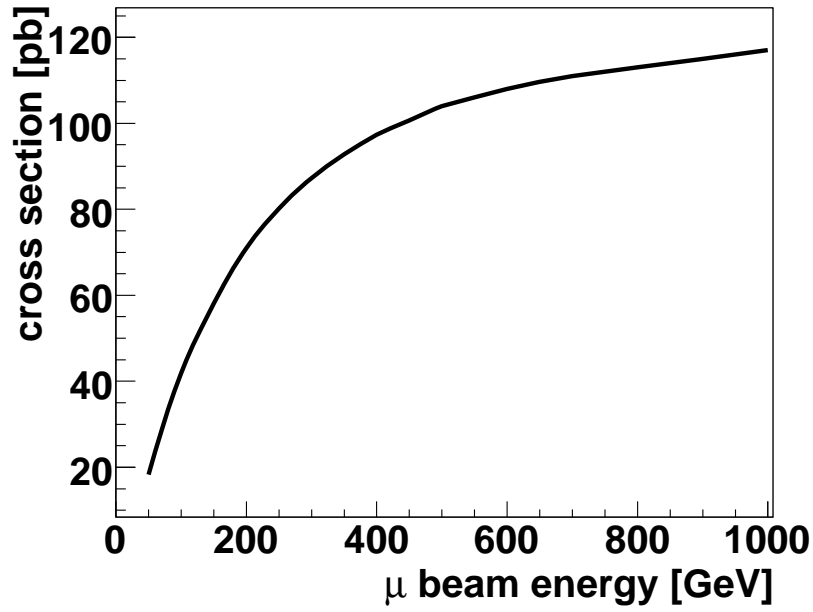


Figure 13: SM cross section for the process $\nu_\mu \mu \rightarrow \nu_\mu \mu$ in a neutrino-muon collider, as a function of muon beam energy.

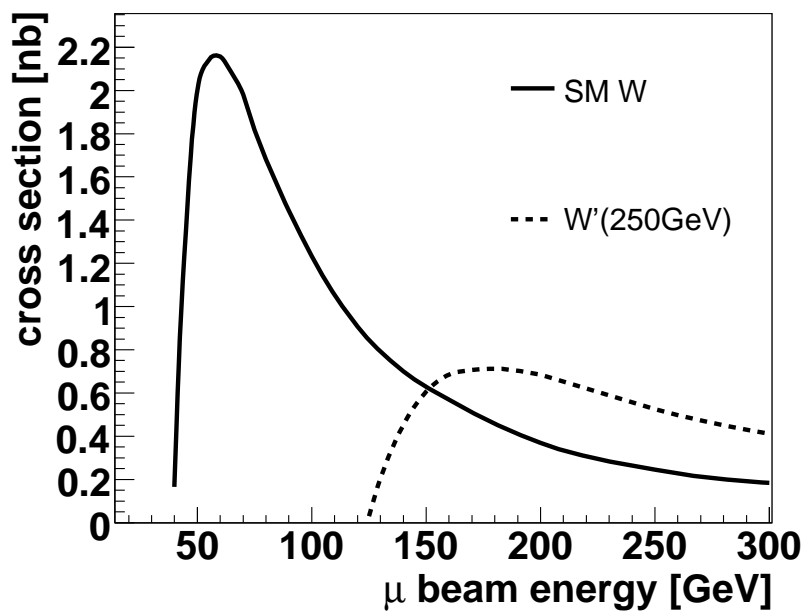


Figure 14: Cross section for neutrino-muon annihilation into a SM W boson or a heavy W' boson in a neutrino-muon collider.

If there is new physics involving an additional heavy charged boson (such as the H^+ shown in Fig. 3 or a heavy W' boson), then this can also be produced in resonance. If this boson couples only to leptons and neutrinos and not to quarks, then it will not be produced at hadron or lepton colliders. In this case a neutrino-lepton collider is the best place to produce such a heavy boson and measure its properties. The dashed line in Fig. 14 shows the cross section for W' boson production with a mass of 250 GeV.

The peak cross section occurs at a beam energy corresponding to about 75% of the boson mass. The dependence of this peak cross section on the mass of the W' boson is shown in Fig. 15. The peak cross section is above 1 nb for W' boson masses up to about 200 GeV and remains above 0.3 nb for masses as high as 1 TeV.

The event rate in a neutrino-muon collider is already quite large with the planned proton driver discussed above. Assuming that in each collision, 10^{12} neutrinos from a μ^+ beam collide with a μ^- beam containing 10^{13} muons, then this yields an instantaneous luminosity of about 10^{27} cm^{-2} per bunch crossing. Current plans for a muon collider assume running at 15 Hz with four bunches. That gives a luminosity of $6 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ which is equivalent to a yearly (10^7 s/year) integrated luminosity of 600 nb^{-1} . This is sufficient to produce both

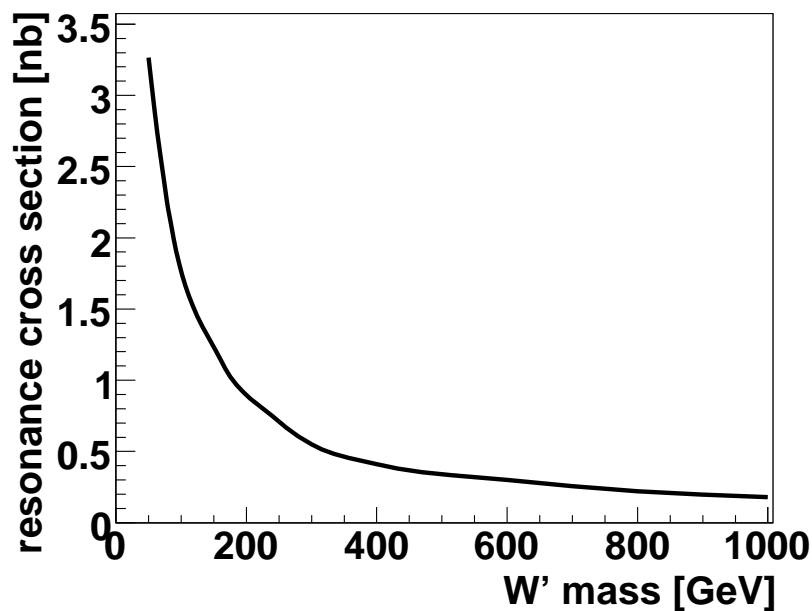


Figure 15: Peak cross section for neutrino-muon annihilation into a heavy W' boson in a neutrino-muon collider as a function of the W' boson mass.

SM W bosons and new W' bosons or any other new particle with similar couplings.

C. Colliding neutrinos and neutrinos

1. LHC

The LHC will accelerate protons to 7000 GeV and collide those in four separate interaction regions. Since the LHC collides a proton beam with another proton beam, both of them can be used to produce neutrino beams and the LHC can become the first neutrino-neutrino collider. This is not possible at the Tevatron where one of the two beams contains antiprotons, and significantly fewer of them than protons. In order to set up a neutrino collider, both proton beams are extracted from the LHC at 7000 GeV and directed onto two different production targets. Pions and kaons are allowed to decay in two separate decay tunnels. The resulting neutrino beams intersect each other at a central detector location. The remaining pions, muons, and other secondaries need to be absorbed or diverted from the neutrino direction through shielding and magnetic fields. The layout of such a machine is shown in Fig. 16.

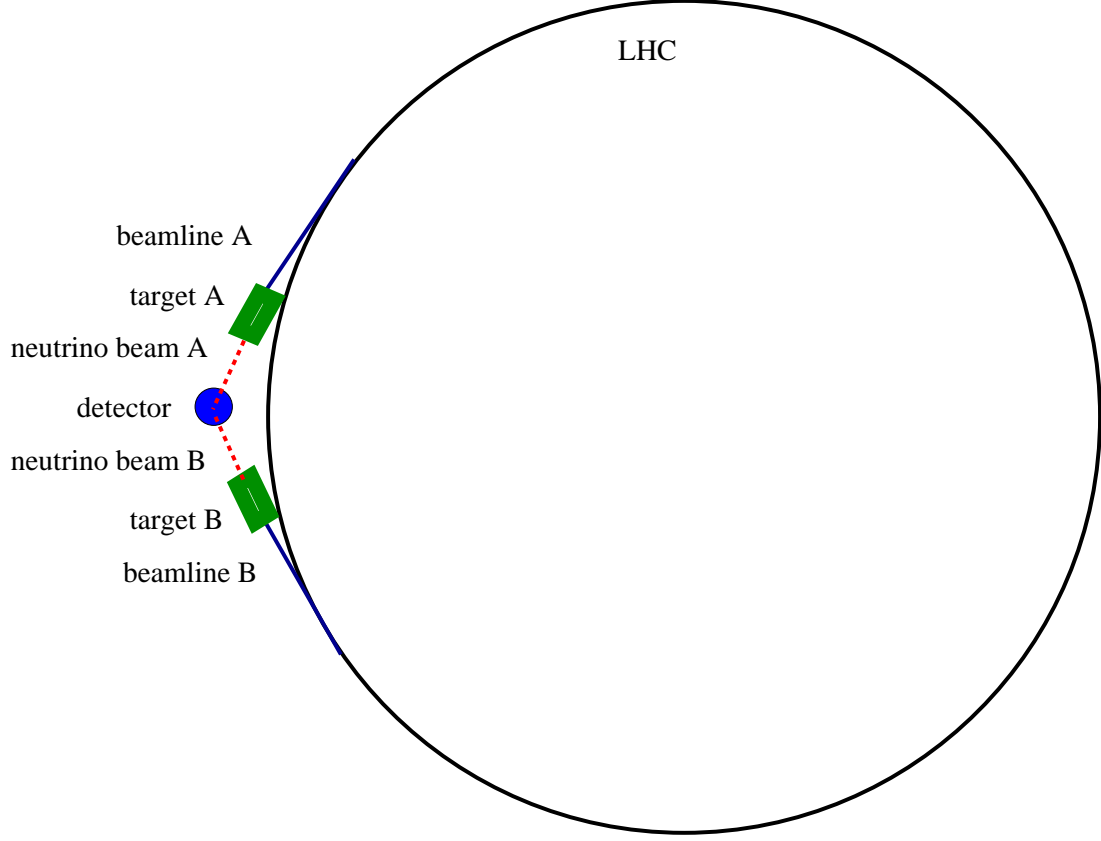


Figure 16: Layout of the LHC accelerator as a neutrino collider, extracting both proton beams and directing them onto two targets such that the resulting neutrino beams collide with each other.

Assuming a similar proton intensity per bunch can be achieved at the Tevatron and at the LHC (10^{14} protons per bunch), then the luminosity per crossing is about $2 \times 10^{24} \text{ cm}^{-2}$. Since there are now two beams that have to be fed from the accelerator chain, the repetition rate will likely be smaller than at the Tevatron and we thus assume about 10^7 collisions per year. This gives an integrated yearly luminosity of $20 \mu\text{b}^{-1}$. The cross section for the process $\nu\bar{\nu} \rightarrow \ell\bar{\ell}$ is about 0.2 nb, thus a setup like this produces about 0.004 di-lepton events per year. In order to produce sizable samples of several tens of events per year, the intensity of the proton beams needs to be increased by about two orders of magnitude.

Similarly to the Tevatron case, in order to achieve integrated luminosities of several pb^{-1} which makes it possible to study more physics processes, the intensity of the proton beams will need to be increased by about three orders of magnitude. While there is currently no clear path to accomplish this, the LHC will run as a proton-proton collider for many years. That time can be spent on increasing the proton luminosity, both at the Tevatron and at

the LHC. By the time the LHC will be finished running and could possibly be converted to a neutrino collider, significantly higher intensities are likely achievable.

2. Muon collider

A muon collider consists of two counter-circulating beams that are brought into collision at one or two interaction points [68, 69]. Each of the muon beams produces a high-intensity, narrowly focused beam of neutrinos, comparable to the neutrino factory. The layout of the two muon beams in the collider has to be changed only slightly in order to achieve collisions of the two neutrino beams. A simple layout is shown in Fig. 17. One of the straight sections of the muon collider is divided into two half-length sections, which have a small angle with respect to each other. Very close to the interaction point, the muon beams are then bent towards each other. The neutrino beams resulting from muon decays in the straight sections are not deflected and continue on a straight path. The neutrino collision point is thus shifted a small distance away from the muon beam direction.

If the angles are chosen such that the two straight sections are almost parallel, then the neutrino interaction region is so close to the muon interaction region that it might be possible to enclose both interaction regions within the same detector. This allows for significant savings in detector cost because only one detector needs to be built rather than two.

An alternative colliding beam setup that provides not one or two but four interaction regions is shown in Fig. 18. In this configuration, the neutrino beams not only collide with each other but also with the muon beams themselves. The four interaction regions are in close proximity to each other: a muon-muon interaction region, a neutrino-neutrino interaction region, and two neutrino-muon interaction regions.

Since the muon collider configuration relies on the same basic storage ring parameters as the neutrino factory, we can use the same parameters as above to calculate the luminosity for this configuration. We assume that in each collision, 10^{12} neutrinos from a μ^+ beam collide with 10^{12} neutrinos from a μ^- beam in an interaction region with a radius of about 1 mm. This yields an instantaneous luminosity of about 10^{26} cm^{-2} per bunch crossing. Current plans for a muon collider assume running at 15 Hz with four bunches. That gives a luminosity of $6 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ which is equivalent to a yearly (10^7 s/year) integrated luminosity of

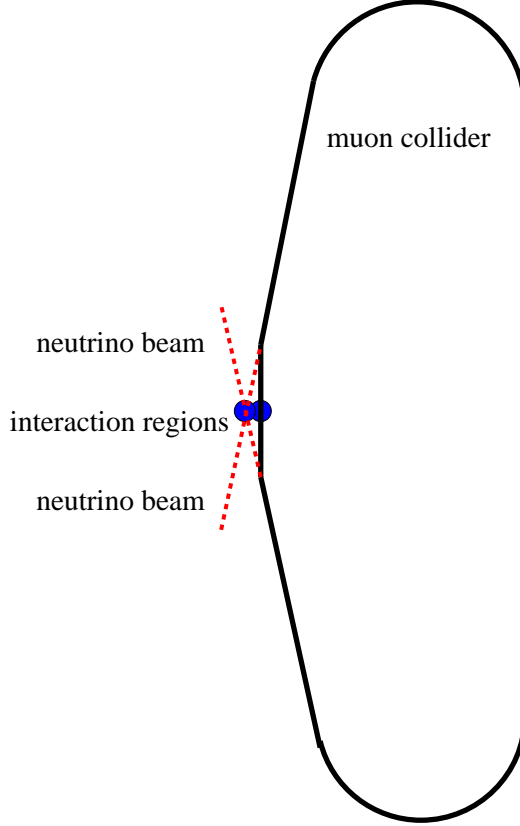


Figure 17: Muon beam configuration to use a muon collider also as a neutrino collider. Each of the two counter-circulating muon beams produces a high-intensity neutrino beam. The two neutrino beams collide with each other in close proximity to the muon collision point. The two interaction regions are indicated by the small circles.

60 nb^{-1} . This is a factor 3000 higher than what could be achieved by converting the LHC to a neutrino collider. Hence, this setup is already sufficient to observe Z boson production in neutrino-anti-neutrino annihilation. Moreover, the neutrino energy in this configuration is significantly higher (a multi-TeV muon collider will produce multi-TeV neutrinos) than in the LHC-based neutrino collider. It will for example be sensitive to higher-mass resonances from new physics in neutrino annihilation.

Fig. 19 shows the cross section for the production of a Z boson at the muon-collider based neutrino collider, as a function of the muon beam energy. The cross section shows a clear peak at a muon energy of slightly less than twice the Z boson mass, similar to W boson production shown in Fig. 14. Also shown is the cross section for production of a heavy Z' boson, with neutrino couplings identical to the SM Z boson but at a mass of 250 GeV.

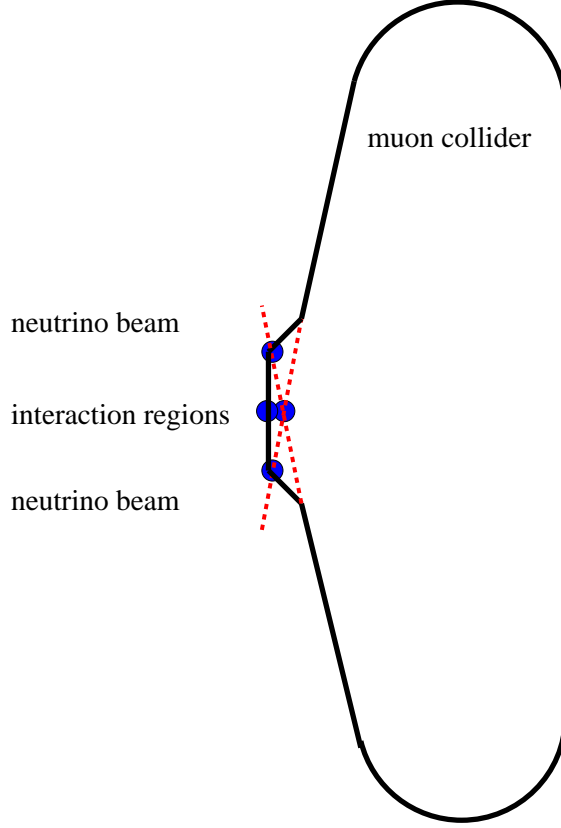


Figure 18: Muon beam configuration to use a muon-muon collider also as a neutrino-neutrino and neutrino-muon collider. Each of the counter-circulating muon beams produces a high-intensity neutrino beam. The two neutrino beams collide with each other and with the muon beam. The four interaction regions are shown as small circles.

In this case the resonance peak is significantly broader, but the cross section is large enough to be able to observe the Z' boson.

Furthermore, since the muon collider is currently only in its planning stages, there is still much room for further improvements. In particular, if the intensity can be increased by another order of magnitude, then integrated luminosities of several pb^{-1} can be reached. Such luminosities extend the sensitivity to new physics in the neutrino sector significantly.

For example, Fig. 20 shows the cross section for the production of heavy neutrinos according to Fig. 5 (a). A νNH^0 coupling strength of 1 is assumed in this example, the exact coupling strength depends on the specific model and might be lower. The neutrinos are produced by 500 GeV muon beams. The cross section in this scenario is in the pb range for heavy neutrinos up to a mass of about 250 GeV, for a Higgs boson mass of 100 GeV. If the

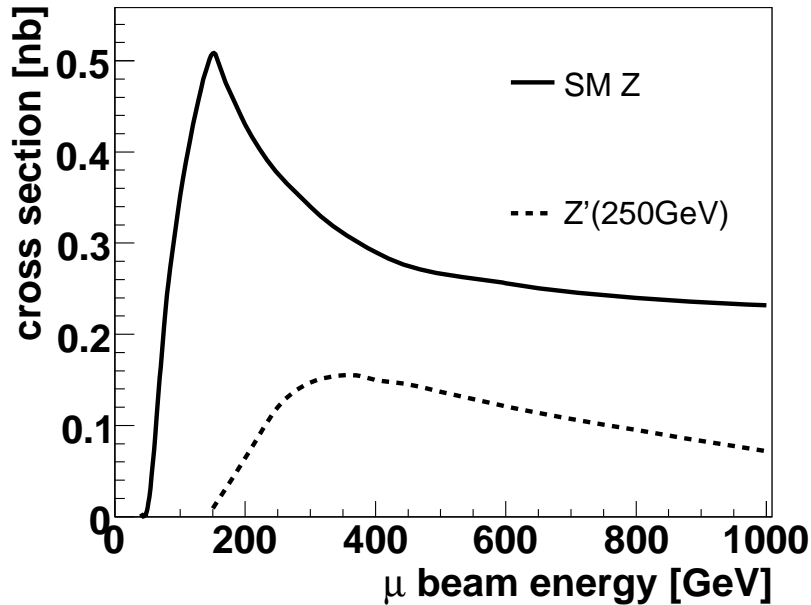


Figure 19: Cross section for neutrino-neutrino scattering to a lepton-lepton final state at a muon collider, as a function of the muon beam energy (solid line). Also shown is the cross section for the production of a heavy Z' boson.

Higgs boson is heavier (1 TeV or more), the cross section is in the fb range and significantly higher luminosity is needed. Single Higgs boson production through loop processes such as shown in Fig. 20 (c) will also be relevant, but the cross section calculation is beyond the scope of this paper.

V. COMMON EXPERIMENTAL CHALLENGES

While neutrino colliders provide exciting measurement opportunities, they also pose unique experimental challenges. As far as the neutrino beam is concerned, there are two main challenges. First and foremost, in order to achieve the required luminosities at a proton accelerator, it is necessary to increase the intensity of the primary proton beams beyond what is currently achievable by several orders of magnitude. Second, experiments will have to deal with many interactions in the detector, due to both beam neutrinos and muons associated with the neutrino beam.

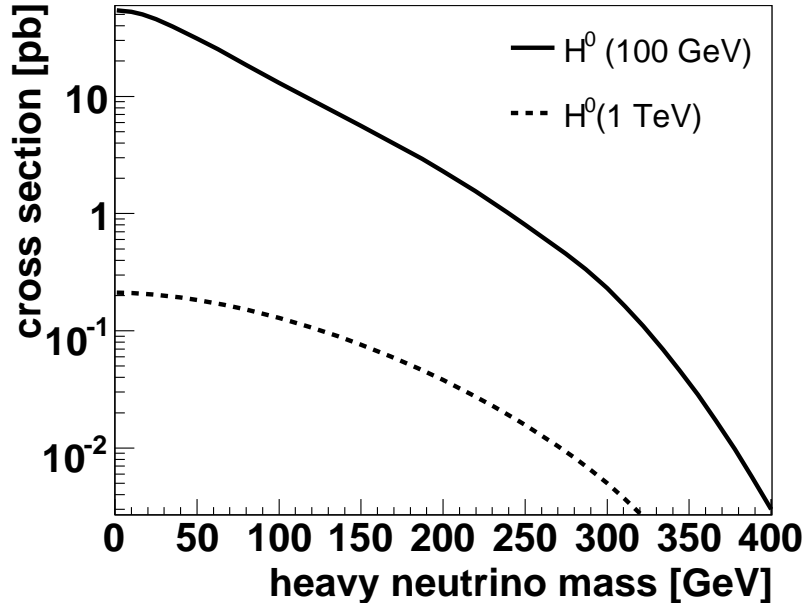


Figure 20: Heavy neutrino pair production cross section in neutrino-neutrino scattering, as a function of the heavy neutrino mass, for two different Higgs boson masses. The neutrinos beams are produced by a muon collider with 500 GeV muon beam energy and the $\nu N H^0$ coupling strength is 1.

A. Associated muon beam

In a proton beam dump experiment there is always an intense muon beam from the decay of pion secondaries associated with the neutrino beam. Since neutrinos possess no charge and cannot be focused, it is imperative for the collision point to be as close as possible to the neutrino production point. This makes it a challenging task to keep muons and other beam-related particles out of the interaction region. In this paper the distance of 10 m has been used to deflect and absorb non-neutrino beam particles. However, as Fig. 6 shows, the neutrino flux does not depend on the distance very strongly and more space can be reserved to deflect and absorb particles without reducing intensity significantly.

The intense muon flux can be separated from the neutrino beam with the help of strong magnetic dipoles to deflect charged particles. This requires powerful magnets upstream of the interaction region. Charged particles other than muons similarly need to be deflected to avoid producing additional showers of hadrons or leptons. The highest energy particles will likely not be deflected very far and it might be necessary to eliminate some detector

material on the two sides to which the charged particles are deflected.

Neutral mesons and baryons can be absorbed by sufficiently thick shielding material in the path of the pion beam. However, any muons passing through magnets or shielding material produces electromagnetic showers. Thus, magnets have to be arranged in such a way that the muons pass through as little material as possible. Minimizing the material in the muon path is also important to avoid muons scattering into the interaction region or detector elements. Hence, a balance has to be found between shielding material and empty space in order to minimize the non-neutrino flux in the interaction region. The feasibility of such a deflecting-magnet setup has been established by the DONUT collaboration [70].

The situation is different from long-baseline neutrino experiments [33, 34], where the associated muon beam is stopped in material in order to prevent it from reaching a near detector. Instead of stopping the muon beam, the goal here is to deflect it through powerful magnets so that it passes by the interaction region and the detector.

B. Interaction region

The neutrino interaction region is the region where the two neutrino beams collide with each other or where the neutrino beam collides with a hadron or lepton beam. When the proton beam hits the production target, the resulting secondary pion beam acquires a large momentum spread and expands in the transverse direction. This spread in pion momentum will be reflected in a spread in neutrino momentum and divergence of the neutrino beam, as shown in Fig. 7. Hence, the neutrino interaction region will have large transverse dimensions compared to other colliding beam experiments.

One advantage of a neutrino-neutrino collider is that it at least in principle doesn't require a vacuum beam pipe at the center and also has no need for magnetic or electric fields close to the interaction region. While the entire detector can at least in principle be instrumented to give true 4π spherical coverage around the collision point, neutrino interactions in the detector make this rather impossible.

There will be many interactions between the neutrino beams and the detector material itself. The neutrino beam is not narrowly focused and there are many neutrinos away from the beam axis. These are mostly at lower energy and thus have a smaller interaction cross section. Nevertheless, their interactions with the detector and shielding material leads to a

large number of energy deposits and hits in the sensitive detector elements. The amount of material in any part of the detector that is exposed to the neutrino beam will need to be minimized in order to reduce these interactions. The path that the neutrinos take will need to be as free of material as possible. Indeed, a large vacuum pipe encompassing the entire neutrino beam is likely needed in order to eliminate neutrino-detector interactions as much as possible.

The transverse dimensions of the neutrino beam are less of a problem in the case of a muon storage ring based neutrino collider. Since the muons have uniform momentum and very little transverse spread, the neutrinos will also be narrowly focussed [61].

C. Detector considerations

The additional interactions in the detector due to beam neutrinos, muons, and other beam-associated particles will likely be the largest source of background to any neutrino collision events. This background needs to be understood in detail and rejected with high efficiency in order to be able to observe neutrino-neutrino collisions. On the negative side, this places serious constraints on possible detector configurations. On the positive side, these neutrino-detector interactions can be utilized to measure the neutrino spectrum, intensity, and beam composition. Close to the collision point, the charged particle tracks from these beam-detector interactions overlap with the charged particle tracks from beam-beam collisions and many detectors will have hits from both types of interactions. Hence, it will be quite challenging for standard particle detectors as they are in use now to work in this environment. Far away from the collision point this is less of a problem because there will be very little neutrino flux. In these regions standard particle detectors should work just fine, for example for calorimetry and muon identification.

Separating the charged particle tracks from neutrino collision from those produced in the detector requires new ideas for sensitive detector elements. There are two main differences between the particles produced in neutrino collisions in the interaction region and the beam-related interactions in the detector that can be exploited here. The first difference is that beam-related interactions typically result in particles traveling in the direction of the beam, whereas neutrino collisions produce particles perpendicular to the beam. The second difference is that the particles produced in collisions typically have higher energy, while particles

produced in beam-related interactions with the detector typically have lower energy.

Exploiting these differences has the following consequences for possible detector configurations: Each detector element should be able to distinguish between different particles traversing it in different directions. One example of a detector that has this capability is a Cherenkov detector. An example of this type of detector is the huge water-Cherenkov detector used in the Kamiokande experiment [2]. It is possible in such a detector to detect and distinguish several particles traversing the detector simultaneously in different directions. Of course the Kamiokande detector is much too large to be used as a single detector element in a colliding beam configuration. The experimental challenge is to design Cherenkov detectors that are sensitive to the direction of a traversing particle while at the same time small enough to be used in the tracking chamber of a colliding beam experiment.

As it turns out, a Cherenkov detector is also well suited to address the second issue of only being sensitive to particles with sufficiently high energy. The size of the Cherenkov radiation light cone is a measure of the particle energy: low energy particles produce a large radius cone while high energy particles produce a narrow light cone. Hence, a detector that can only detect light cones below a certain radius is also a detector insensitive to low energy particles.

VI. CONCLUSIONS

In order to study the origin of neutrino masses it is necessary to explore neutrino interactions at much higher energies than observed so far. In this paper, we have investigated several colliding beam scenarios involving neutrinos, colliding them both with other fermions and with other neutrinos. It is clear that existing technology is not sufficient to produce neutrino beams with high-enough intensity to be used in colliding beam configurations. Increases of at least two orders of magnitude are necessary in the intensity of primary particles (protons) used to generate neutrino beams.

If such increases can be achieved, then neutrino colliders become an attractive possibility. They allow for a first direct measurement of the neutrino annihilation cross section to Z bosons and several other electroweak measurements. A neutrino-neutrino collider based on the LHC will be the first machine sensitive to new physics in the neutrino sector and possibly the origin of neutrino mass. The high-intensity, high-energy neutrino beam produced

at a muon collider improves upon the reach of the LHC by several orders of magnitude. Neutrino-neutrino collisions can be observed already with muon colliders currently under consideration. And while these neutrino-neutrino collisions might not be the main motivation for building a muon collider, they nevertheless provide excellent opportunities to understand neutrinos better and can easily be incorporated into muon collider designs.

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